Distribution System Hydraulic Modeling Analysis Examines System Issues and Identifies Operational Solutions

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ABSTRACT

The Town of Framingham Public Works Department has contended with a large number of service and main breaks. Between January 2013 and the end of March 2014 the Town repaired over 150 water main and service breaks. Recently, Town officials, municipal employees, and consulting engineers worked together to update an eight-year-old water distribution model and perform transient analyses to identify factors contributing to water main breaks. Model test runs revealed that the age of the system, poor pipe material quality and incidents of water hammer were responsible for most of the water main breaks. Based on these findings, the Town formulated a plan to reduce the frequency of water main breaks by redrawing zone boundaries, replacing old pipe, and planning for strategic improvements going forward..

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Framingham: A Brief History

As shown in Figure 1, located 23 miles outside of Boston, Framingham is one of the oldest communities in Massachusetts. It was founded in 1662. At present, its residential population is approximately 68,000 making Framingham the largest town in Massachusetts by population and in many ways comparable to more urban cities though the overall landscape having both rural and urban characteristics. The Town serves residential, commercial, institutional, and industrial sectors, with much of its commercial customers located along the Route 9 corridor, which connects Boston to Worcester. Commercial and industrial components of the Town contribute an estimated 10,000 person increase in daytime population. The Town is also home to two colleges; a major biotechnology firm, Genzyme; and many other businesses.

The origin of Framingham's water main system dates back to the late 1800's, similar to many New England communities. During this time period, communities began to build water supply systems for public health and sanitation reasons. The Town was much

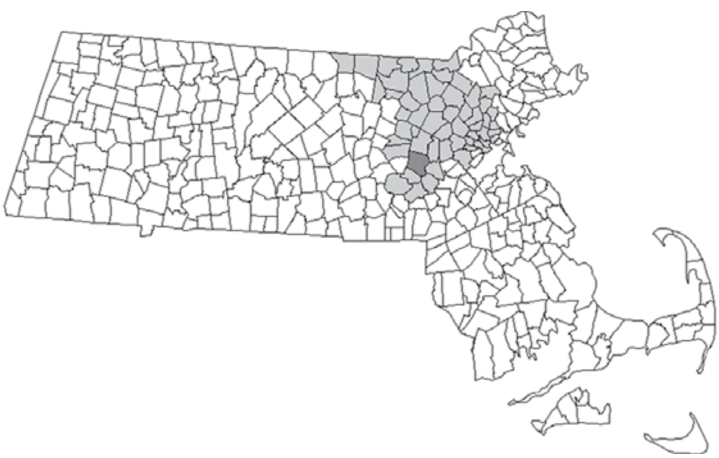


Figure 1. Location of Framingham, MA

smaller at the turn of the twentieth century with a population of approximately 11,300 residents. Framingham's population doubled between 1910 and 1930, and doubled again by 1960 to nearly 45,000 residents. The Town has continued to see nominal growth since the 1970's. While additional water mains were laid to compensate for this growth, war effort demand for scrap metal meant that these pipes were often made of lesser quality materials than current day standards, including thinner cast iron pipes. The age of the pipes, as well as their material, is believed to play a major role in the current rate of water main breaks.

The Town of Framingham's Water System

The Town purchases its water supply from the Massachusetts Water Resources Authority (MWRA) and distributes this water through the Town owned and operated infrastructure. As of 2015, the Town maintains approximately 260 miles of water main, six water storage tanks, and seven water pumps stations. This system serves 18,000 water accounts. This is a significant sized system to maintain, and its advanced age contributes to the demand for regular and intensive maintenance and repairs. The system currently has to meet an average water daily

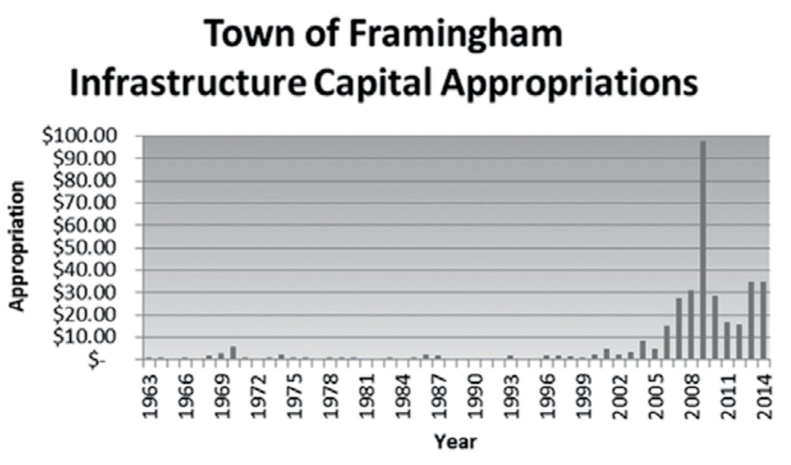
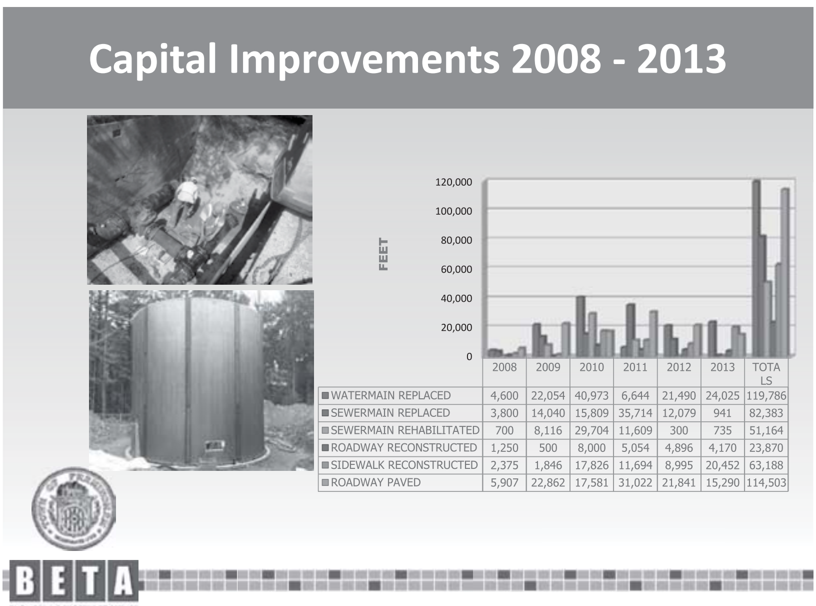


Figure 2. Town of Framingham infrastructure capital appropriations



	2008	2009	2010	2011	2012	2013	TOTALS
WATERMAIN REPLACED	4,600	22,054	40,973	6,644	21,490	24,025	119,786
SEWERMAIN REPLACED	3,800	14,040	15,809	35,714	12,079	941	82,383
SEWERMAIN REHABILITATED	700	8,116	29,704	11,609	300	735	51,164
ROADWAY RECONSTRUCTED	1,250	500	8,000	5,054	4,896	4,170	23,870
SIDEWALK RECONSTRUCTED	2,375	1,846	17,826	11,694	8,995	20,452	63,188
ROADWAY PAVED	5,907	22,862	17,581	31,022	21,841	15,290	114,503

Figure 3. Capital improvements 2008-2013

Figure 4. Image of water main improvements

demand of approximately seven million gallons per day, and a peak water demand of ten million gallons per day.

From the 1960s to the early 2000s, the Town, like many New England communities, made minimal infrastructure investments. This meant that the aging system did not receive repairs and upgrades needed to accommodate changing demands of the population, industries, and commercial users in Town. Infrastructure investment is depicted in Figure 2. Town of Framingham Infrastructure Capital Appropriations shows municipal infrastructure expenditure by year from 1963 to 2014.

In 2007, the Town received an Administrative Consent Order and a Settlement Agreement for the wastewater system from the Department of Environmental Protection (MADEP) and the MWRA, respectively. The consent order required the Town make improvements to mitigate sanitary sewer overflows and the settlement agreement required high hydrogen sulfide system concentrations to be reduced or eliminated. The Town took it upon themselves to look at the water and sewer systems together holistically as a Town Asset and began assessing flaws through modeling and master planning efforts. In 2007 the Town of Framingham began working with BETA Group, Inc. (the engineer) on a water system master planning effort to address systems weaknesses, including system age and plan for much-needed infrastructure improvements.

Since 2008, the Town has replaced approximately 10 linear miles of distribution and transmission mains and associated appurtenances. Figure 3, Capital Improvements 2008-2013, depicts the investment made in these infrastructure improvements since 2008.

The Town remains committed to an ongoing program of capital improvements over the next 20 years to upgrade the water system to adequately serve the modern community requirements. Expected expenditures over the next 10 years are depicted in, Figure 5, Capital Improvements 2016-2026. The Town has planned out continued capital improvements from 2016 through 2026 with an estimated annual budget of $8-15 million per year. The Town is continually reevaluating and reprioritizing projects as the conditions of infrastructure change and the Town's water needs change. This graphic depicts overall expenditures dropping off over the next decade. However, the Town expects that additional projects will be identified or designed that may alter that trend as the years progress with new projects to be planned and added beyond 2026.

The Town attributes its success in funding and implementing the capital improvement program to its public education campaign. The campaign has been successful in educating the public on the need to upgrade and improve the system and the value that the asset provides the community. The Town has found that the public will embrace and commit to municipal spending on infrastructure when they are well informed on the rationale and when a community culture of

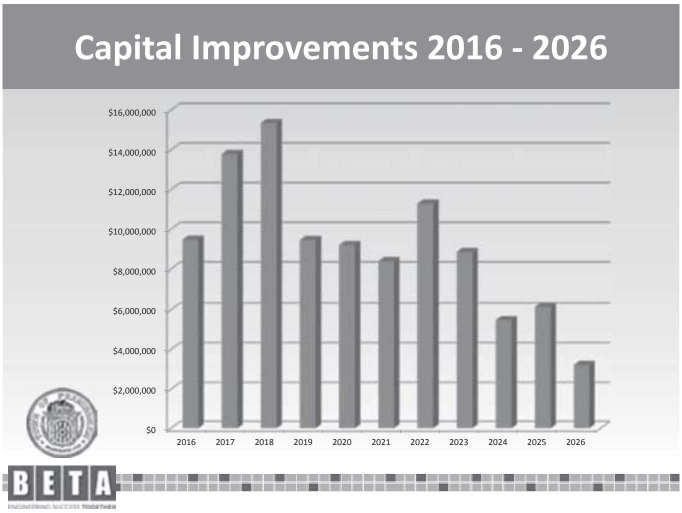


Figure 5. Capital improvements 2016-2026

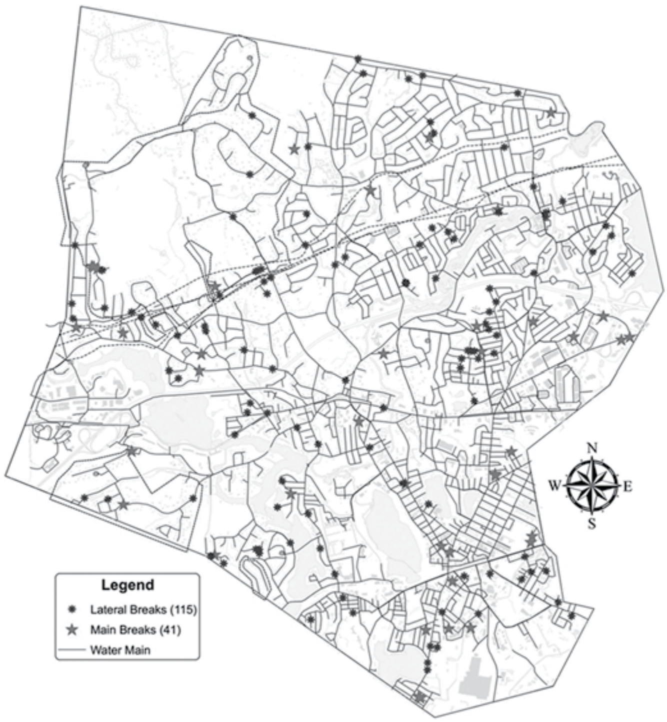


Figure 6. Breakdown of water main breaks in the Town of Framingham

prioritizing community infrastructure improvements is cultivated.

Water Main Breaks

The Town has experienced an "unusually high" number and frequency of water main breaks with over 150 service and water main breaks between January 2013 and the end of March 2014. It became crucial that the maintenance of the system be addressed in a more holistic manner. High rate of breaks reprioritizes staff from regular operations to emergency repairs. Worse still, these breaks often occurred during off-hours, which increased departmental overhead and budget strained by unanticipated overtime expenses. The Town needed to spend less

Figure 7. Town of Framingham water zones

time repairing emergency water main breaks and more time addressing regular maintenance and implementing the needed infrastructure improvements.

In addition to the budget constraints, water main breaks were also contributing to increased water loss, which increases the expense of the water supplied to the Town. Further, residents and businesses were inconvenienced each time the DPW had to temporarily shut off their water service access while teams fixed system breaks. The Town also lost revenue, as residents are not billed when they have temporary water service that does not pass through the installed meter. Taken together, these factors were negatively affecting the community on a variety of levels. This is a familiar struggle for many Towns across the country that also struggle with maintaining aging infrastructure and suffer frequent water main breaks.

Municipal water system age, pressure, geometry, materials, and other variables can affect system performance. Town officials knew that system age and quality of the materials used contributed to the high number of water main breaks, as did the installation methods employed. Operational issues, depth of frost, geological issues including soil type and bedrock, as well as hydraulic transients, such as water hammer, all were suspected to play a role in the Town's frequent water main breaks. The Town anticipated that engineering analysis could examine these hypotheses and identify factors that were causing these issues, so that an improvement plan could be implemented.

Updating the 2007 Model

The initial model was created as part of the 2007 master plan. In the eight years that followed, the Town has invested significantly on improvements to the water system. By 2014 the 2007 model needed substantial updating to accurately represent the existing system and begin evaluating frequent service and water main breaks. The Town and BETA worked together to update the model and identify system characteristics that may be contributing to the frequent breaks, and how they may be incorporated in the model analysis. New development since 2007 was added, along with updates to water mains and stations that had already been rehabilitated.

Pressure zone boundaries and zone redundancies were suspected in playing a role in the frequency of water main breaks. The Town has 5 distinct pressure zones, as indicated in Figure 7, Town of Framingham Water Zones: Main town zone, Beebe zone in the Northwest quadrant, and three smaller zones. BETA looked at the boundaries of the five zones to determine whether

Figure 8. Debris from water mains

Figure 9. Pitot tube fragment from water mains

unequal zone boundary distribution was causing problems, performed a water hammer analysis to locate transients, and evaluated whether system fluctuations within MWRA impacted water main breaks in the Town.

Engineer Field Tests – Model Calibration

BETA worked with Town field personnel to implement a testing program over two weeks. Testing was generally conducted at night to minimize disruption to residents and businesses. Field testing consisted of hydrant flow and pipe condition testing. During calibration and flushing exercise, a lot of debris was flushed from the system. Figure 8, Debris From Water Mains, and Figure 9, Pitot Tube Fragment From Water Mains, show how some of the debris that came out of water mains during this flushing exercise and damaged the pitot.

Results of these field tests were compared to predicted results as produced by the updated model. Where these results differed BETA ran a series of calibration test runs to identify friction factors (C-values) representative of the current condition of the existing water system. This step served to calibrate the model and ensure that subsequent analyses would be representative of the water system. This information was used to update the WaterGEMS model as well as run a water hammer analysis.

Field testing when compared to the model further revealed three areas with suspected closed water main valves. This finding allowed DPW staff to focus field investigations and was able to identify at least one closed valve and another closed section of pipe in need of repair. Two broken valve boxes were also identified for replacement and further investigation.

Water Hammer Analysis Results

Water Hammer, transients, can occur for a variety of reasons, including flushing activity, poorly designed water valves, municipal blackouts causing all of the water pumps to simultaneously stop functioning, and closing valves or hydrants too quickly when operating. The telltale symptom, which may be familiar to those readers who live in older homes, is the sound of concussion or banging as water inside the pipe stops abruptly as in shutting off a faucet quickly. When water moves in the pipe and is suddenly stopped (as in the case of shutting off a fire hydrant too quickly), a pressure wave can be created in the water main, which can bounce back and forth within the distribution system. As the wave bounces within a water main, the wave's intensity can build depending on the geometry of the piping/bends/fittings and the frequency of the wave, which can result in pressure building within the pipe. When the pressure of the water hammer exceeds the amount of pressure the pipe can withstand, the pipe or appurtenance fails at its weakest point producing a break in the system.

Modeling runs were able to identify water mains that had a moderate to high propensity

Figure 10. Likelihood of transients in the Town of Framingham water mains

for water hammer. The modeled system was analyzed for water hammer by simulating the operation of hydrants for either fire or maintenance condition by applying an instantaneous flow followed by a quick shutoff at various locations throughout the distribution system. Transient pressure experienced by a pipe varies and fluctuates depending on the location and magnitude of the source of the transient. This figure shows the compilation of reactions observed in the distribution system after numerous transient analysis model runs were conducted. The water hammer analysis identified areas of low, medium, and high water hammer probability as shown in Figure 10, Likelihood of Transients in Town of Framingham Water Mains.

Green lines represent pipe where no issues were found, while blue areas had a moderate potential for water hammer. Transients within these pipes may need to be addressed in the future but were not a priority. Red lines on Figure 10, Likelihood of Transients in Town of Framingham Water Mains, indicated areas where there is high potential for water hammer of more than 150 pounds per square inch of pressure (psi). In at least two cases, predicted transient pressure could be as much as 500 psi. New pipe properly installed is generally operated under 100 psi but may be rated for 250-350 psi. Transients pose a serious problem and identifying systems weak points has helped the Town prioritize repairs and minimize future water main breaks in known high-risk neighborhoods.

During the modeling, the project team discovered that one zone boundary (the areas of Angelica Drive and Lanewood Street) had dead ends that were very susceptible to water hammer. Pipes in this area were normally under low pressure of around 25 psi; however, if the pipe in this area was subjected to a water hammer transient it would expose the pipes to hundreds of pounds of pressure and almost certainly cause a break. This poses a real hazard as well as a major inconvenience to residents in the neighborhood and thus a high priority fix.

Pipe Material Analysis

Prior to running field tests, BETA and DPW had suspected that the thin walled cast iron pipe that was laid from 1950 to 1975 played a large

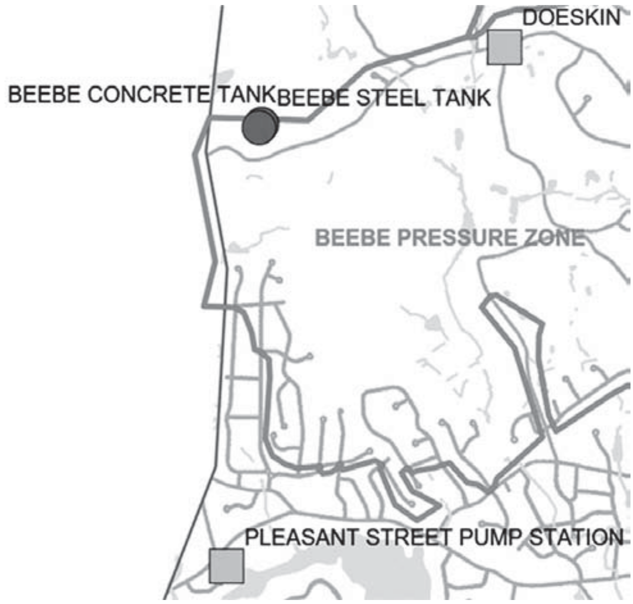


Figure 11. Proposed zone boundary shift

role in the high incidence of water main breaks. Record data confirmed that old cast iron pipes in the system did in fact play a large role in the frequency of water main breaks. Cast iron pipes installed prior to 1950 accounted for 24 percent of water main breaks while cast iron pipes installed between 1950 and 1975 accounted for 61 percent of water main breaks.

At the time of analysis, there were almost 1 million feet of cast iron pipes still in use. The Town's water main rehabilitation approach had been to clean and reline these pipes to extend their lifespan. However, BETA determined through pipe material analysis, that replacing the pipe instead of cleaning it was a more appropriate solution. Water main rehabilitation planning should prioritize this pipe for rehabilitation by replacement over rehabilitation as it appears to fail at a higher frequency. Removing the cast iron pipe from the system will help solve most of the Town's water main break issues. That said, the sheer quantity of vintage cast iron pipe still in use means that the replacement process will take a significant number of years to complete.

Zone Shift Recommendations

Findings of the transient modeling revealed that there was one zone boundary issue as briefly mentioned above. The boundary located south of the Beebe Zone at the Angelica Drive and Lanewood Street area creates a dead end condition in both of these streets. Records indicated two water mains recently in Alan Street, a cross street of both Angelica and Lanewood, but this main is located outside the Beebe Zone in the Town Zone.

BETA developed a plan to mitigate the concern for transients in the area. They recommended moving the zone boundary to Alan Street. This creates a loop that alleviates the stress of the transient condition caused by the dead-end pipe sections. This also improves the average day condition water pressure on Angelica and Lanewood, which was low in the existing condition due to the dead-end water mains. However, it should also be noted, the water mains on these streets are cast iron of the 1950-1975 vintage and are susceptible to breaks and are recommended to be replaced as described above.

Figure 11 illustrates the revised zone boundary.

Surge Valve Recommendations

Recommended improvements to mitigate transients from occurring included installation surge relief valves. BETA found that putting in strategic surge relief valves, designed to open automatically to alleviate pressure changes associated with a transient, would minimize the pressure and possibly prevent the occurrence of a break. A total of ten locations were identified across three pressure zones. Four locations in the Beebe zone along the Town zone boundary, one location

Figure 12. Location of proposed strategic surge relief valves

in the Goodnow Zone, and five locations in the Town Zone were identified.

BETA has prioritized the first five recommended implantation locations. The Town is planning to implement the first strategic surge relief valves in the coming year with a plan to add surge relief valves in order of importance. Figure 12, Location of Proposed Strategic Surge Relief Valves, shows both the locations of proposed surge relief valves and their order of importance..

Air Relief Valve Recommendations

BETA also made recommendations for strategic air release from the system. Air release would improve capacity issues and reduce water hammer concerns (See Figure 13, Manual or Automatic Air Release Locations). The Town is naturally hilly, with the highest elevation located in the Northwest corner of the community. These topographic changes mean that air pockets naturally develop as the water main pipes follow the topographic landscape throughout the Town, and there are a large number of localized high points across Town.

Air pockets in the system can contribute to incidents of transients. As a pressure wave hits an air pocket, it is unable to push through the air, and reflects back in the direction from which it came potentially leading to higher pressures. Without the air pocket, the wave stands a chance of naturally dissipating or of reaching a strategic surge valve and forcibly dissipating. The Town does not yet have a plan to move forward with installation of air valves, but is developing an air release strategy as part of regular maintenance. The Town plans to bleed air out of the system during routine flushing work. Either strategy will help reduce the impact of water hammer and may in turn be expected to reduce the incidence of water main breaks..

Conclusion

The Town found that updating the model after eight years of extensive system improvements was necessary to perform the evaluation and analysis of the current system. It is recommended that infrastructure improvements be regularly logged and updated in the model to maintain an accurate and up-to-date portrait of water system; something that the Town is committed to moving forward as the results proved valuable in preventing future breaks. The update to the Town's water model combined with transient analysis has provided the Town with a clarified understanding and strategic plan to begin proactively addressing the many breaks experienced in recent years.

Figure 13. Manual or automatic air release locations

One of the most significant findings was the correlation between a specific pipe type, 1950-1975 vintage cast iron, and water main breaks. This pipe type was associated with 82% of the water main breaks during the study period. The Town plans to implement a policy to prioritize the replacement of this pipe as it has proven to fail at a higher frequency than older pipe and pipes of different materials.

BETA has also recommended that the Town of Framingham continue to implement the 2008 master plan recommendations, as was originally planned. However, instead of simply cleaning and lining the vintage cast iron pipe as originally recommended BETA recommends replacement of all 1950-1975 pipes with ductile iron pipe. Doing so may greatly reduce the number of water main breaks.

All zone boundaries were evaluated within the analysis and were generally found to be suitable, with the exception of one change in the boundaries of the Beebe Zone. This change would improve water pressure, eliminate two dead ends, and create a loop in an area of the prone to water hammer incidents (Figure 11). The pipe in this loop will need to be replaced as the existing cast iron may not hold up in the higher pressure zone. It is also recommended that the Town consider adding surge relief at key locations throughout the distribution system. The Town should also consider implementing an air release strategy or installing air relief valves to prevent air pockets from contributing to water hammer. To support the infrastructure improvement program, it is recommended the model be updated regularly to include all infrastructure improvements and maintain this valuable resource. Keeping the model up to date allows the Town to have an accurate high-level overview of what is going on and to make informed decisions regarding improvements. Changing community demographics and industrial and commercial shifts in the Town will affect water system needs and should also be considered as part of the regular model updates. This resource will allow the Capital Improvement Plan to be continuously updated and validated in support of the Town's needs, thus becoming a living document.

Framingham's leaders and residents are committed to making infrastructure improvements to increase the quality of life and steward Town water resources. The new modeling effort offers recommendations and findings that will greatly reduce the strain water main breaks put on the system and staff. By adopting a similar comprehensive approach, other New England communities with unusually high water main breaks may also find relief.